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Short-wavelength acuity: optical factors affecting detection and resolution of blue–yellow sinusoidal gratings in foveal and peripheral vision

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Abstract

Previous studies have indicated that peripheral achromatic grating resolution is limited by the sampling density of the neural array (sampling limited), and largely unaffected by large amounts of optical defocus and significant changes in luminance. Under certain conditions, peripheral short-wavelength sensitive (SWS) grating acuity is also sampling limited. We wished to determine how the sampling-limited nature of SWS-driven grating resolution was affected by changing optical defocus and stimulus luminance. Using SWS-cone isolation techniques, detection and resolution acuity were measured for sinusoidal gratings under varying levels of stimulus mean luminance and optical defocus in the fovea and at 20° eccentricity. From 1.4 down to 0.3 cd/m^2 peripheral detection acuity was superior to resolution acuity, accompanied by observations of aliasing: there was little change in resolution performance throughout this range. For defocus up to 3–4 dioptres, peripheral detection acuity was superior to resolution but fell steadily: resolution performance remained flat throughout the same range. Unlike achromatic acuity, foveal resolution performance displayed some robustness to defocus but to a lesser degree than the periphery. Peripheral SWS-driven resolution remains sampling limited for large changes in stimulus luminance and optical defocus, and should thus be useful as a clinical test of SWS-driven ganglion cell density.

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1. Introduction

Previous studies (Anderson, 1996a,b; Wang, Thibos, & Bradley, 1997) have indicated that, in peripheral vision, resolution acuity, but not detection acuity, for high contrast sinusoidal gratings is largely unaffected by optical defocus up to around 3 dioptres. The reason for this is the sampling-limited nature of the peripheral resolution task, whereby it is possible for a high spatial frequency grating to be above the threshold for detection by percipient elements in the retina and be simultaneously beyond their ability to correctly resolve either its orientation (Anderson, 1996a,b; Anderson, Evans, & Thibos, 1996; Thibos, Cheney, & Walsh, 1987; Thibos, Still, & Bradley, 1996; Williams, Artal, Navarro, McMahon, & Brainard, 1996) or drift direction (Anderson, Drasdo, & Thompson, 1995; Anderson & Hess, 1990a,b). This superiority of detection acuity over resolution acuity is typically accompanied by the observation of aliasing phenomena, whereby a grating of high spatial frequency masquerades as one of lower spatial frequency and/or different orientation (Anderson, 1996a,b; Smith & Cass, 1987; Thibos et al., 1996; Thibos, Walsh, & Cheney, 1987; Williams, 1985a,b; Williams et al., 1996) or drift direction (Anderson & Hess, 1990a,b). In foveal vision the phenomenon of aliasing is not observable under normal viewing conditions because spatial frequencies higher than the resolution (Nyquist) limit of the retina do not pass through the optics of the eye (Campbell & Green, 1965; Campbell & Gubisch, 1966) and any grating which can be detected can simultaneously be resolved. Further evidence for the

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sampling-limited nature of peripheral grating resolution is the fact that, while detection acuity for gratings in peripheral vision declines steadily with decreasing contrast, resolution acuity for the same target is largely unaffected by changes in contrast down to 10–20% (Anderson, 1996a,b; Thibos et al., 1996).

Since peripheral resolution for achromatic gratings is directly related to retinal sampling density, in particular the density of the coarsest array in the sequence of retinal neurons, the ganglion cells (Thibos et al., 1987), several attempts have been made to estimate localised retinal ganglion cell density, employing measures of grating resolution acuity. These measurements display good agreement with predicted measures based on anatomical counts of retinal ganglion cell density at the same locations (Anderson, 1996a,b; Anderson & McDowell, 1997; Anderson, Wilkinson, & Thibos, 1992; Anderson et al., 1995; Anderson & Hess, 1990a,b; Thibos et al., 1987).

The fact that peripheral achromatic resolution acuity is unaffected by significant amounts of optical defocus is not only further evidence that the task is sampling limited, but is of clinical importance in that newer perimetry tests which employ measures of peripheral resolution to detect ganglion cell sampling loss in diseases like glaucoma (Anderson & McDowell, 1997; Anderson & O'Brien, 1996; Thibos, 1997) are not as susceptible to optical defocus as conventional perimetric methods which employ measurements of differential light threshold for the detection of spot stimuli (Anderson, McDowell, & Ennis, 2001; Herse, 1992).

We recently conducted a study indicating that resolution acuity is also sampling limited for gratings that selectively stimulate the short-wavelength sensitive (SWS) cone pathway (Anderson, Zlatkova, & Demirel, 2002). Again, evidence for this came from the fact that detection acuity was significantly higher than resolution and was accompanied by observations of chromatic aliasing within the SWS isolation range in both fovea and periphery. Further, when SWS-driven resolution values were compared with localised morphological counts of different retinal cell types, there was a close agreement with the predicted resolution based on counts of small bistratified ganglion cell density, the cell receiving its input from the blue cones.

This finding also has clinical importance. In recent years, reports of selective damage to the SWS pathway in early glaucoma (Heron, Adams, & Husted, 1987; Sample, Boynton, & Weinreb, 1988) has led to the development of short-wavelength automated perimetry (SWAP) (Demirel & Johnson, 1996; Johnson, Adams, Casson, & Brandt, 1993; Johnson, Brandt, Khong, & Adams, 1995; Sample, Juang, & Weinreb, 1991; Sample, Taylor, Martinez, Lusky, & Weinreb, 1993; Sample & Weinreb, 1990; Sample & Weinreb, 1992) in an attempt to detect the condition at an earlier stage. This clinical test, which uses broadly similar SWS-isolating conditions (blue spot stimuli projected on bright yellow adapting background) measures the sensitivity of the SWS system and has shown some potential for earlier glaucoma detection (Johnson et al., 1993; Johnson et al., 1995; Sample et al., 1993; Sample & Weinreb, 1990). Unfortunately it suffers from the problem of age-related lens yellowing which lowers short-wavelength sensitivity, and hence the ability to detect neural damage. In addition, like conventional white-on-white perimetry, it remains susceptible to the effects of optical defocus.

Swanson (1989) measured foveal grating resolution acuity in a large number of subjects using short-wavelength pathway isolating stimuli and found that poor refractive correction significantly lowered performance. He also found that simulating pre-receptoral filtering began to have an effect on acuity after 0.5 log unit attenuation of the blue stimulus luminance. With clinical application in mind, we wanted to determine the effect of simulated lens yellowing on resolution acuity thresholds for SWS-isolating gratings in both the fovea and periphery: employing an initially sampling-limited task, how susceptible is the test to the effects of short-wave absorption? In addition, how does increasing optical defocus affect SWS-driven resolution performance: will it also prove to be as robust to the effects of defocus as measurements of achromatic resolution?

2. Methods

2.1. Subjects

Acuity measurements were made for two experienced subjects (two of the authors). Both were close to emmetropic foveally and had no ocular abnormalities or measurable colour vision deficiencies, as assessed by the Ishihara Test and the City University Colour Test. Before commencing measurements, the subjects were refracted by an experienced optometrist using retinoscopy at 0° and 20° in the temporal horizontal retina. To remove accommodation and simultaneously permit a sufficiently high level of retinal illumination, during all sessions subjects were dilated and cyclopleged using 1% cyclopentolate, which resulted in an 8–9 mm pupil, verified before and after each experimental session. No artificial pupil was used.

2.2. Stimuli and apparatus

The experimental set-up was closely similar to our previous study (Anderson et al., 2002). Short-wavelength stimuli were generated using a Visual Stimulus Generator VSG2/3 (Cambridge Research Systems, Rochester, UK) on a 21″ high-resolution monitor (Sony 500PS), which was checked for linearity (γ-correction).

The monitor had a frame rate of 100 Hz, a pixel resolution of 1024×768 and a screen size of 30×40 cm. Stimuli were fairly narrow-band blue sinusoidal grating patches with the same mean luminance as their blue background, generated using only the blue gun of the monitor (see spectral output curve Fig. 1): no other filter was used for the stimulus. The maximum mean luminance of the blue grating was 1.4 cd/m^2 (71 td) and the luminance contrast was 96%. Luminance and spectral measurements were made with a PR650 Spectrascan Spectra Colorimeter at the eye position. The stimulus temporal luminance distribution was a ramp with total duration of 1 s, including a rise and decay time of 0.3 s.

Detection and resolution acuities were measured in the fovea and at 20° in the temporal retina. The grating patch was circular with a diameter of 2° in the fovea and 5.4° in the periphery. The preliminary measurements showed that these patch sizes allowed at least 2–3 cycles to be displayed even at the lowest spatial frequencies tested. Fixation was maintained on the monitor using two small, closely spaced, vertically aligned black squares where the subject fixated the central gap. In any one session the monitor, fixation target and stimulus were all positioned to permit the appropriate retinal location to be tested. At each location the previously determined peripheral refractive correction was positioned in line with the short-wavelength stimulus and modified subjectively using a maximum contrast procedure, in order to correct for both chromatic shift of focus and cycloplegia caused by the cyclopentolate.

The adapting background apparatus was positioned at right angles to the monitor and principally consisted of a halogen projector with a long-wavelength pass yellow filter (OG530, half maximal absorption at 530 nm) positioned in front of the projector lens (see Fig. 1). The yellow light was projected through a white diffusing screen and, to minimise stray light, the projector and filter were contained within a box that was light-tight except for the front end with the diffusing screen. The observer viewed the yellow background through a beam-splitter, positioned in front of his/her face, angled at 45°. The yellow background covered ≈40° of the observer's central field of view, significantly greater than that of the monitor (30° maximum) at all times. Yellow background luminance was set at 600 cd/m^2 (3×10^4 td) in order to adapt efficiently the long-wavelength-sensitive (LWS) and medium-wavelength-sensitive (MWS) cones thus leaving the grating stimulus visible only to the SWS cones. We found in our previous study (Anderson et al., 2002) that this luminance was high enough to isolate SWS cones without reducing much the SWS-cone contrast due to very intensive long wavelength

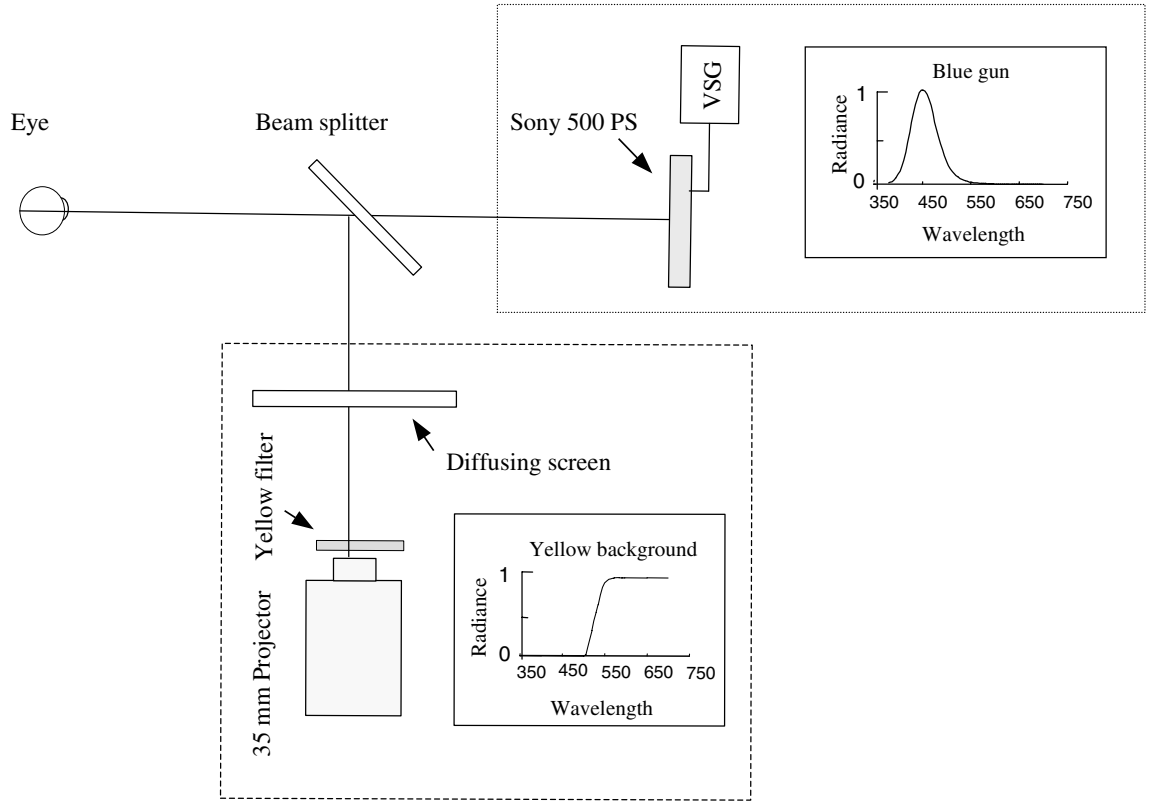

Fig. 1. Experimental set-up for measurement of SWS acuity.

Table 1
Luminances of the blue grating background (in cd/m^2) and SWS-cone contrasts (in %) for the same gratings superimposed on a yellow background with constant luminance (600 cd/m^2)

Luminance of the blue background	0.14	0.33	0.56	0.95	1.41
SWS-cone contrast	16.5	31.7	44.1	57.2	66.5

stimulation. The background luminance was verified before the commencement of each session using an OptiCAL photometer (Cambridge Research Systems).

The contrast of the blue-on-yellow gratings seen via SWS cones alone (SWS-cone contrast) was calculated in order to assess their effectiveness with respect to the SWS-cone system. The spectral radiance of the blue gun and the yellow background were measured using the PR650 Spectrascan Spectra Colorimeter. The SWS-cone excitation due to the blue grating plus the yellow background was calculated as an integral of the product of the combined spectrum with Smith and Pokorny's S-cone fundamental (Smith & Pokorny, 1975). The Michelson contrast was then obtained. The calculated SWS-cone contrasts are shown in Table 1 for the range of luminances of the blue grating background.

2.3. Psychophysical procedure

The subject sat in a darkened room and viewed the stimulus monocularly with the right eye, the left eye being patched. At the start of each session he/she adapted to the yellow background for at least 2 min. The viewing distance was 1.5 m for foveal measurements in order to generate sufficiently high spatial frequencies on the monitor without luminance artefacts. For peripheral measurements, the monitor was placed at 0.7 m from the subject, and the stimulus was positioned at 20° in the horizontal nasal field (temporal retina).

Detection acuity was measured using a temporal two-alternative forced choice (2AFC) procedure. Each trial consisted of two temporal intervals marked by an audible tone and separated by 1 s. One of the intervals, randomly chosen, contained the grating stimulus and the other contained a uniform field with the same mean luminance. The subject had to indicate if the grating was presented in the first or second interval by pressing the appropriate button. The stimulus orientation was 135° oblique. Three correct responses resulted in an increase in spatial frequency and one incorrect response resulted in a decrease in spatial frequency. No feedback was given. The starting stimulus spatial frequency was determined to be slightly supra-threshold and changed in 0.8 dB steps. The threshold acuity was calculated as the mean of 6 reversal values. This procedure provided an estimation of the threshold corresponding to 79% correct responses. Three runs were performed in separate sessions for each stimulus configuration and averaged.

Resolution acuity was measured using a spatial 2AFC procedure. The grating was presented on each trial in one of two orientations (45° or 135° oblique). The subject had to indicate if the orientation of the grating, which was random and of equal probability, was to the right or to the left by pressing the appropriate button. Since acuity is identical for gratings oriented obliquely with respect to the fovea (Anderson et al., 1992; Rovamo, Virsu, Laurinen, & Hyvarinen, 1982) the subject received no cue to orientation based on differences in stimulus visibility. Each interval was preceded by an audible tone. The same three-up, one-down staircase procedure was used. The threshold was calculated as the mean of 6 reversal values and, again, three runs were performed on separate sessions and averaged.

Each subject was permitted some practice prior to the data collection. These practice sessions served to familiarise the subjects with the task and continued until the performance was found to be asymptotic.

2.4. Simulation of lens absorption

Since retinal illumination decreases with reduced lens transmittance, to simulate the lens absorption we studied the effect of the blue background luminance on acuity. With normal optical correction, detection and resolution thresholds were measured for blue monitor mean luminances ranging from 0.14 to 1.4 cd/m^2, keeping the grating mean luminance the same as that of the blue background. This was accomplished by varying the voltage to the blue gun, which caused the spectral output to vary in a linear fashion. The yellow background was kept constant at 600 cd/m^2. Mean luminance was verified before the start of each session using the OptiCAL photometer.

2.5. Optical defocus

Detection and resolution measurements were made under maximum blue luminance conditions after the introduction of optical defocus ranging in power from 0 to +4 dioptres in 0.5 dioptre steps. This was accomplished by placing an additional spherical trial lens in front of the right eye in line with the grating stimulus.

3. Results

Fig. 2 plots the variation in detection and resolution performance with blue background luminance in the fovea and periphery for both subjects. In the fovea, from 1.4 cd/m^2 down to 0.14 cd/m^2 detection performance declines in a steady manner. However, down to 0.33 cd/m^2 for both subjects, there is little or no change in res-

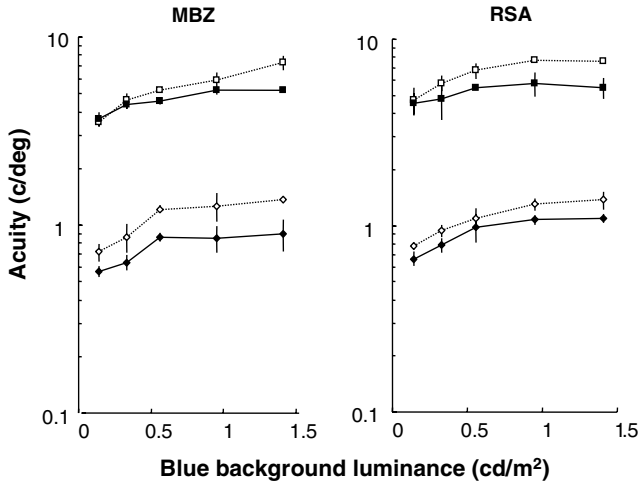

Fig. 2. SWS detection acuity (open symbols) and resolution acuity (closed symbols) as a function of blue grating background luminance in the fovea (squares) and 20° the periphery (diamonds) for both subjects. Upper curves. Error bars represent 95% confidence intervals.

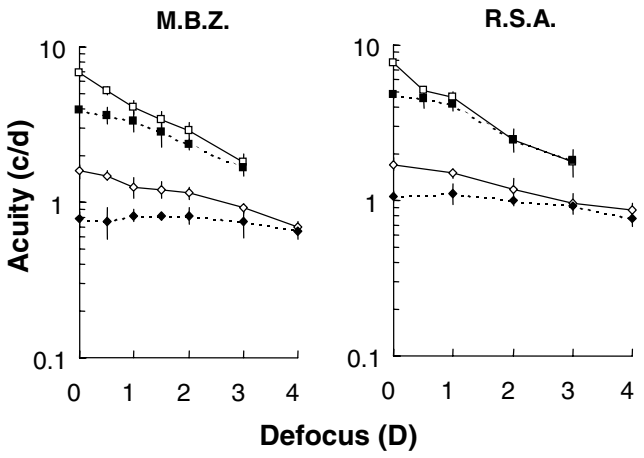

Fig. 3. SWS detection acuity (open symbols) and resolution acuity (closed symbols) for different amounts of optical defocus in the fovea (squares) and 20° in the periphery (diamonds) for both subjects. The error bars represent 95% confidence intervals.

olution acuity with luminance and it is significantly lower than detection acuity ($p < 0.05$, paired t-test) in that range. Both subjects observed aliased components of the grating, which appeared as blue–yellow "splotchy" pattern. Detection and resolution performances converge at 0.33 cd/m^2, after which the two decline together. The aliasing phenomenon was no longer observed.

At 20° eccentricity, detection performance declines less markedly with luminance down to 0.56 cd/m^2, but reduces more quickly thereafter. Resolution performance remains largely unaffected until 0.56 cd/m^2, after which it declines quickly but, unlike in the fovea, remains significantly lower ($p < 0.05$, paired t-test) than detection performance all the way down to 0.14 cd/m^2 with both subjects reporting the presence of aliasing. The overall change of the acuity with the blue background luminance is higher in the retinal periphery (36–39%) than in the fovea (18–25%).

Fig. 3 plots detection and resolution acuity with varying degrees of optical blur for both subjects. It can be observed that, in the fovea, under zero defocus conditions, detection acuity is significantly higher than resolution. As optical blur is introduced, detection acuity declines immediately and steadily with increasing defocus. Resolution acuity is little affected until around 1 dioptre, after which it declines more rapidly with increasing blur. At around 0.5 dioptres for subject RSA and 1.5 dioptres for subject MBZ, resolution and detection performance converge, after which both are identical ($p > 0.05$, paired t-test) and decline together.

In the periphery, detection acuity again declines immediately and steadily with increasing optical blur, but resolution acuity remains largely unaffected until around 3–4 dioptres defocus and again aliasing was continuously reported in that range. Resolution acuity was significantly lower than detection acuity ($p < 0.05$, paired t-test). After 4 dioptres for MBZ and 3 dioptres defocus for RSA the difference between resolution and detection performance becomes insignificant ($p > 0.05$, paired t-test).

4. Discussion

Similar to achromatic acuity (Anderson, 1996a,b; Ennis & Anderson, 2000; Wang et al., 1997), peripheral SWS acuity appears to be robust both to significant decreases in stimulus luminance and increases in optical blur. The superiority of detection acuity over resolution, accompanied by observations of chromatic aliasing, reported by all observers under higher luminance and lower blur conditions in both fovea and periphery, is evidence for the sampling-limited nature of the resolution task. Also, the fact that peripheral resolution acuity remains unaffected by significant decreases in retinal illumination or increasing blur is further evidence that the task is sampling limited at this location. The reduction in blue background luminance results in decreasing the contrast of the grating seen by SWS cones (Table 1) but the resolution acuity remains constant throughout a large range of blue luminance levels. So long as the stimulus is sufficiently above the contrast detection threshold of the responding retinal ganglion cells, moderate changes in stimulus contrast due to either of these factors will have little or no effect, and resolution performance will depend solely on the density of the underlying sampling array. When contrast is reduced further, the stimulus reaches a point where it becomes unresolvable because it can not first be detected. At this

point detection and resolution performance become equal.

However, SWS acuity differs somewhat from achromatic acuity in the fovea. Looking first at the foveal curves in Fig. 2, although the aliasing zone is generally narrower in the fovea both detection and resolution acuity display considerable robustness to declining luminance. This is not the case for foveal achromatic acuity where detection and resolution acuity exhibit identical performance and decline immediately and sharply with either decreasing illumination (Ennis & Anderson, 2000) or increasing optical blur (Anderson, 1996a,b; Wang et al., 1997). As the optics in the fovea do not pass spatial frequencies higher than the spatial sampling limit of the total neural array (optically limited), both detection and resolution for achromatic stimuli decline because of the reduced contrast. However, the resolution limit of SWS-cone system remains considerably lower than the limit set by the optics. The Nyquist frequency of SWS cones in the fovea is estimated to be 5 c/deg (Curcio et al., 1991) in close agreement with resolution acuity values found by psychophysical interferrometric studies bypassing the eye's optics (Williams, Collier, & Thompson, 1983) or under normal viewing (Anderson et al., 2002; Hess, Mullen, & Zrenner, 1989). The resolution values in the present study obtained at high retinal illumination and low blur are also close to this value, thus suggesting that resolution performance has been limited by the sampling density of neural array rather than by reduced contrast. Although the large pupil used by us could deteriorate the eye's optical quality thus moving the optical limit closer to the resolution limit, the optics with an 8 mm pupil pass up to 8 c/deg in the fovea (Artal & Navarro, 1994), still higher than the Nyquist frequency of the SWS cones and subsequent neural arrays. The lower optical quality in this case would reduce the aliasing region without affecting the sampling-limited resolution acuity. In the present study an aliasing zone was apparent in the fovea up to only 0.5 dioptres for subject RSA and 1 dioptre for subject MBZ. At 20° in the periphery, the modulation transfer function (MTF) of the eye's optics is considerably better than the limits of the sampling array density. Even without correction for off-axis astigmatism, the MTF was estimated to be 0.9 at 1 c/deg (Navarro, Artal, & Williams, 1993; Williams et al., 1996) which is close to the typical SWS-resolution acuity values found by us in the periphery. Thus, the optical limitations become negligible as evidenced by the constancy of the resolution performance in a large dioptric range up to 4 diopters.

The change in the blue background luminance had similar effect on both subjects although subject MBZ (being older) had an increased lens density than subject RSA, as assessed by the method described in the companion paper. This will result in greater initial absorption in the short-wavelength region, and in an acuity reduction at higher level of the blue luminance than for RSA. The only effect due to this factor was observed in the fovea where, as stimulus luminance decreases, foveal detection and resolution performance become equal at 0.3 cd/m^2 for subject MBZ but not till 0.14 cd/m^2 for subject RSA, although the difference was not statistically significant. Swanson (1989), starting with a 7 cd/m^2 blue grating, found that foveal resolution performance declined after around 0.5–1.0 log units of attenuation. This is sooner than we are observing presently but may be due to a couple of factors. Firstly, Swanson's study used natural pupils which would be very small when exposed to the bright yellow adapting background, resulting in a much lower starting retinal illumination for the blue stimulus, and thus an earlier observed deficit as attenuation increases further. Secondly, he did not optically correct for viewing distance before measuring acuity, meaning the subjects were probably starting from a lower retinal contrast, and thus acuity would decline sooner as blue luminance decreased. At 20° in the periphery resolution acuity began to decline after around 0.6 cd/m^2 but remains sampling limited down to the lowest luminance level used by us. This observation is less easily explained: it may be that, while the task remains sampling limited, not all blue–yellow cells have equal sensitivity and some begin to 'drop-out' before others, thus lowering the effective sampling density.

These findings have important clinical implications. One of the most commonly reported weaknesses of SWAP is its susceptibility to absorption by age-related lens yellowing, making the separation of optical and neural visual loss much more difficult. The same goes for optical defocus. The human eye exhibits significant peripheral refractive error that is virtually impossible to correct in a clinical situation. A SWS-isolating resolution perimetry test such as described in this study, which is robust to both moderate degrees of blue absorption owing to lens yellowing, as well as peripheral optical defocus would negate the requirement for accurate localised refractive correction. This in turn could prove very useful in the study of SWS-driven ganglion cell loss as a result of age, macular degeneration, or other ocular conditions such as glaucoma, unconfounded by the effects of optical filtering. In addition, by comparing resolution acuity using both achromatic and SWS-isolating stimuli we should be better able to determine if the above mentioned conditions really do result in a selective loss of cells associated with one or other mechanism.

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